

Evidence for the $\psi(5S)$ and $\psi(4D)$ $c\bar{c}$ vector resonances

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Abstract

We present evidence for the $\psi(5S)$ and $\psi(4D)$ $c\bar{c}$ vector resonances in experimental data published by the Belle and BaBar Collaborations. Central masses and resonance widths are estimated.

Keywords: New charmonium vector resonances; electron-positron data; $\psi(5S)$ and $\psi(4D)$ states; threshold effects; open-charm meson-meson channels; open-charm baryon-baryon channel.

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Since the late 1970s or early 1980s, it has been recognized that the interpretation of strong-interaction scattering and production data is much more involved than what is actually being practised in data analysis. At present, one of the main obstacles to steady progress in low-energy strong-interaction physics is the very poor handling of threshold enhancements in reactions where multihadron systems are produced. Very often, the corresponding signals are not even considered in data analysis, since their amplitudes are well below some arbitrarily defined background. Moreover, just above the thresholds of the specific channels selected for analysis, and where the threshold enhancements are usually well visible, the amplitudes are fitted with simple Breit-Wigner shapes and the associated central masses and widths. Thus, such enhancements are — by definition — declared resonances.

In this respect, an important observation was made by the BES Collaboration in Ref. [1]. To our knowledge, BES was the first to realize that the $\psi(3770)$ cross section is built up by two different amplitudes, viz. a relatively broad signal and a rather narrow $c\bar{c}$ resonance. For the narrow resonance, which probably corresponds to the well-established $\psi(1D)(3770)$, BES determined a central resonance position of $3781.0 \pm 1.3 \pm 0.5$ MeV and a width of $19.3 \pm 3.1 \pm 0.1$ MeV (their solution 2). If the latter parameters are indeed confirmed, it would be yet another observation of a quark-antiquark resonance width that is very different from the world average (83.9 ± 2.4 MeV [2] in this case), after a similar result was obtained by the BaBar Collaboration in Ref. [3], for $b\bar{b}$ resonances. Concerning the broader structure, the BES Collaboration indicated, for their solution 2, a central resonance position of $3762.6 \pm 11.8 \pm 0.5$ MeV and a width of $49.9 \pm 32.1 \pm 0.1$ MeV. The

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signal significance for this new enhancement is 7.6σ (solution 2). It was explained as a possible diresonance [4] or heavy molecular state [5].

Moreover, in the latter BES publication, the existence of conflicting results with respect to the branching fraction for non- $D\bar{D}$ hadronic decays of the $\psi(1D)(3770)$ was emphasized. On the one hand, the total branching fraction for exclusive non- $D\bar{D}$ modes has been measured to be less than 2% [6, 7]. But on the other hand, for inclusive non- $D\bar{D}$ decay modes, values of about 15% have been found [8, 9]. According to BES, this apparent discrepancy may partially be due to the assumption that the line shape above the $D\bar{D}$ threshold is the result of one simple resonance. Now, in Ref. [10] we have shown that the broader structure is most likely caused by a non-resonant contribution to the production amplitude, thus lending further support to the idea that the $\psi(1D)(3770)$ enhancement consists of two distinct signals, one of which is nothing else but a threshold effect.

Several of the new enhancements in production cross sections share the common property that they occur at — or just above — an important threshold. The most recent example, viz. the $J/\psi\phi$ enhancement observed and baptized as $Y(4140)$ by the CDF Collaboration [11], appears right above the $J/\psi\phi$ threshold. The enhancement in the $e^+e^- \rightarrow \Lambda_c^+\Lambda_c^-$ cross section, reported by Belle [12], occurs right above the $\Lambda_c^+\Lambda_c^-$ threshold. The $Y(4260)$ enhancement in the $e^+e^- \rightarrow J/\psi\pi^+\pi^-$ cross section, observed by BaBar [13], is right on top of the $D_s^*D_s^*$ threshold. The $X(3872)$ enhancement [14] in $B^\pm \rightarrow J/\psi K^\pm\pi^+\pi^-$ decay lies just above the DD^* threshold.

In Fig. 1, we show the production cross sections for the reaction $e^+e^- \rightarrow D^+\bar{D}^{*-}$, published by the Belle Collaboration [15], using initial-state radiation (ISR). The signal was not further analysed by Belle, for which they gave the following reason:

Since a reliable fit to the cross sections [obtained above] requires a solution to a non-trivial and model-dependent problem of coupled channels and threshold effects, we do not report results here.

This is symptomatic for the quite desperate situation in which low-energy strong-interaction physics finds itself at present. We have no doubts that the major part of the amplitude at about 4.0 GeV is due to threshold enhancements. However, contrary to the single threshold enhancement under the $\psi(3770)$, here the amplitude contains several enhancements, viz. $D^\pm D^{*\mp}$ at 3.880 GeV, $D_s^\pm D_s^{*\mp}$ at 3.937 GeV, $D^{*\pm} D^{*\mp}$ at 4.02 GeV and $D_s^\pm D_s^{*\mp}$ at 4.081 GeV. It will certainly not be a simple task to conveniently parametrize these mutually interfering threshold enhancements, which in their turn interfere with the resonances of the quark-antiquark propagator.

In Ref. [16], we derived a precise relation between the formalism of non-exotic meson-meson scattering due to a resonating s -channel quark-antiquark propagator in the intermediate state, and the deformed $q\bar{q}$ resonance spectrum owing to the inclusion of infinite chains of meson loops. Moreover, in Ref. [17] we deduced an amplitude for production processes, resulting in a complex relation [18] between production and scattering amplitudes. The latter relation is formally equivalent [19] to the real relation of Au, Morgan, and Pennington [20], but with an important difference: whereas the coefficients of the complex relation [18] are of a purely kinematical origin, the real coefficients of Ref. [20] contain the scattering amplitudes themselves [21]. As a consequence, one does not find a distinct threshold enhancement in the formalism of Ref. [20].

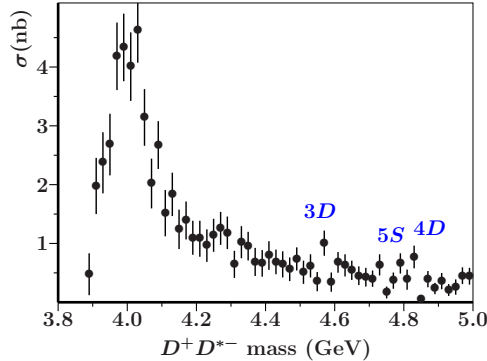


Figure 1: Event distributions for the reaction $e^+e^- \rightarrow D^+ \bar{D}^{*-}$, as published by the Belle Collaboration [15].

Furthermore, in Ref. [22] we studied the shapes of open-bottom thresholds. However, we must admit that the case of a clear separation of $b\bar{b} \leftrightarrow (b\bar{u}/\bar{d}) + (\bar{b}u/d)$ and $b\bar{b} \leftrightarrow (b\bar{s}) + (\bar{b}s)$ thresholds is much simpler than the comparable case of open charm, in which the corresponding channels are partly overlapping, as $m_D < m_{D_s} < m_{D^*}$, whereas $m_B < m_{B^*} < m_{B_s}$. Consequently, practical expressions for data analysis are not yet at hand.

We can observe some structure in the data [15] presented in Fig. 1, at invariant masses in the interval 4.7–4.9 GeV, where the $\psi(5S)$ and $\psi(4D)$ $c\bar{c}$ vector resonances are expected [23] to reside, besides an enhancement in the $\psi(3D)$ region. Here, despite our still very incomplete description of threshold enhancements, we shall continue our program to search for new vector $c\bar{c}$ states in the data, and indicate where to look. For now, we shall concentrate on the $\psi(5S)$ and $\psi(4D)$ resonances.

In Ref. [12], the Belle Collaboration announced the observation of a near-threshold enhancement, by studying the $e^+e^- \rightarrow \Lambda_c^+ \Lambda_c^-$ cross section. The experimental analysis resulted in a mass and width for this enhancement of $M = (4634^{+8}_{-7}(\text{stat.})^{+5}_{-8}(\text{sys.}) \text{ MeV}$ and $\Gamma_{\text{tot}} = 92^{+40}_{-24}(\text{stat.})^{+10}_{-21}(\text{sys.}) \text{ MeV}$, respectively [12], with a significance of 8.8σ . An intriguing aspect of this experimental observation is that the main signal lies close to the $\Lambda_c^+ \Lambda_c^-$ threshold, making an understanding of this structure a highly topical issue [24].

The $e^+e^- \rightarrow \Lambda_c^+ \Lambda_c^-$ cross section is given in Fig. 2, where one observes, besides the threshold enhancement, two well separated resonances, i.e., most probably the $\psi(5S)$ and $\psi(4D)$ $c\bar{c}$ vector resonances as discussed in Ref. [24].

Modelling the $\Lambda_c^+ \Lambda_c^-$ enhancement might of course be done by considering a full wave function with all possible components, viz. $c\bar{c}$ states, charmed-meson pairs, and charmed-baryon pairs. Such a wave function will have a large $\Lambda_c^+ \Lambda_c^-$ component under the enhancement. Nevertheless, it will not give rise to a resonance pole in the full coupled-channel scattering amplitude, unless, accidentally, there is a dynamically generated resonance pole in this invariant-mass region. Now, in view of the large non-resonant contribution to the $\Lambda_c^+ \Lambda_c^-$ enhancement, we do not consider the occurrence here of a dynamically generated resonance very likely, which is in line with a similar conclusion by Bugg [25]. Recently, it was claimed [26] that the enhancement could be consistent with

the $\psi(2S)f_0(980)$ molecular picture of the $Y(4660)$, taking into account the $\Lambda_c^+\Lambda_c^-$ final-state interaction. In our opinion, it certainly does not represent a state of the $J^{PC} = 1^{--}$ $c\bar{c}$ spectrum as advocated in Refs. [27, 28].

Earlier, however, the BaBar Collaboration had published [13] interesting data for the

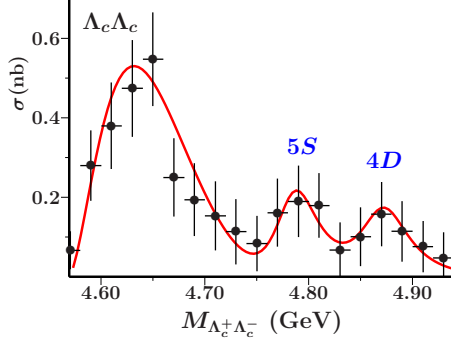


Figure 2: Event distributions for the reaction $e^+e^- \rightarrow \Lambda_c^+\Lambda_c^-$, as published by the Belle Collaboration in Ref. [12].

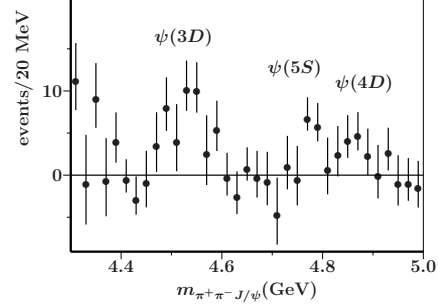


Figure 3: Event distributions for the missing signal [29] in the reaction $e^+e^- \rightarrow \pi^+\pi^- J/\psi$, using data published by the BaBar Collaboration [13].

reaction $e^+e^- \rightarrow \pi^+\pi^- J/\psi$, using ISR. These data, which passed unnoticed for a few years, showed that, upon studying the missing signal [30], one could observe (see Fig. 3) the $\psi(5S)$ and $\psi(4D)$ $c\bar{c}$ vector resonances, besides a clear signal from the $\psi(3D)$ [29].

More recent data from Belle and BaBar reveal clearer resonance shapes for the $\psi(5S)$ and $\psi(4D)$. Here, we study data for the invariant-mass distributions of the $D^0 D^{*-} \pi^+$ and $D^0 D^- \pi^+$ systems, published by Belle in Refs. [31] and [32], respectively, and also of the $D^* \bar{D}^*$ system, published by BaBar [33].

In Figs. 4 and 5, we show our fit to the relevant data of the $D^0 D^{*-} \pi^+$ [31] and $D^0 D^- \pi^+$ [32] invariant-mass distributions, respectively, for $M(5S) = 4.82$ GeV, $M(4D) = 4.90$ GeV, $\Gamma(5S) = 65$ MeV, and $\Gamma(4D) = 50$ MeV, in both cases. Errors in these values will be of the order of the bin sizes, viz. 40 MeV. In Fig. 6, we present our fit to

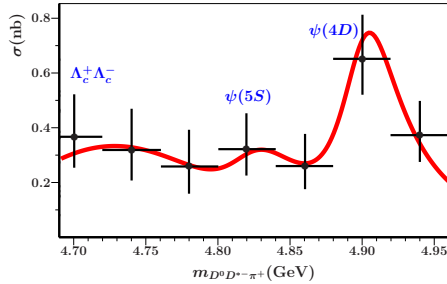


Figure 4: Fit to the $D^0 D^{*-} \pi^+$ invariant-mass distribution for the Belle data of Ref. [31].

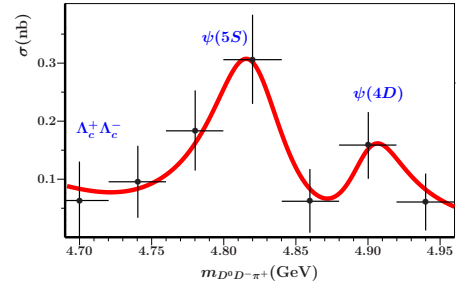


Figure 5: Fit to the $D^0 D^- \pi^+$ invariant-mass distribution for the Belle data of Ref. [32].

the relevant data of the $D^* \bar{D}^*$ invariant-mass distribution [33], for $M(5S) = 4.81$ GeV,

$M(4D) = 4.93$ GeV, $\Gamma(5S) = 100$ MeV, and $\Gamma(4D) = 55$ MeV (bin sizes are 25 MeV here).

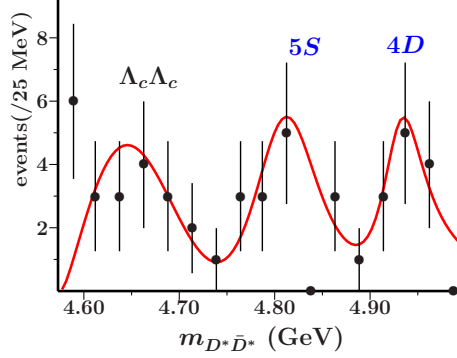


Figure 6: Fit to the $D^*\bar{D}^*$ invariant-mass distribution for the BaBar data of Ref. [33].

Previously [10], we had found $M(5S) = 4.784$ GeV, $M(4D) = 4.871$ GeV, $\Gamma(5S) = 55$ MeV, and $\Gamma(4D) = 60$ MeV (bin sizes of 20 MeV) for the Breit-Wigner parameters of the $\psi(5S)$ and $\psi(4D)$, in order to fit the $\Lambda_c^+\Lambda_c^-$ mass distribution of Fig. 3.

The latter results merely demonstrate that Breit-Wigner parameters are only useful for narrow resonances, which in all channels have approximately the same appearance. For many strong processes, resonance poles can only be determined through analytic continuation of the scattering amplitude obtained from multichannel coupled equations. As a consequence, it does not make much sense either to average over the various Breit-Wigner parameters we have obtained so far for the $\psi(5S)$ and $\psi(4D)$ resonances.

In conclusion, we can state that we have found clear signs of the $\psi(5S)$ and $\psi(4D)$ $c\bar{c}$ vector resonances in published data. Depending upon the channel in which these new states are analysed, they will show up with central masses of $M(5S) \approx 4.78\text{--}4.81$ GeV and $M(4D) \approx 4.87\text{--}4.93$ GeV, while their widths will be in the ball park of $\Gamma(5S) \approx 50\text{--}100$ MeV and $\Gamma(4D) \approx 50\text{--}60$ MeV.

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